UNIVERSITY OF BRISTOL
FACULTY OF ENGINEERING

First Year Examination for the Degrees of
Bachelor and Master of Engineering

May/June 2023 3 HOURS

AVDASI 1: Fundamentals of Aerospace
AENG 10004

This paper contains 14 questions. Answer all questions.

The maximum for this paper is 100 marks.

TURN OVER ONLY WHEN TOLD TO START WRITING

ONLY NON-PROGRAMMABLE CALCULATORS MAY BE USED

Data sheet

$C_L = \frac{L}{\frac{1}{2}\rho V^2 S}$ $\quad C_D = \frac{D}{\frac{1}{2}\rho V^2 S}$ $\quad C_M = \frac{M}{\frac{1}{2}\rho V^2 Sc}$ $\quad C_H = \frac{M}{\frac{1}{2}\rho V^2 S_f c_f}$

$C_{L_{2D}} = \frac{L_{2D}}{\frac{1}{2}\rho V^2 c}$ $\quad C_{D_{2D}} = \frac{D_{2D}}{\frac{1}{2}\rho V^2 c}$ $\quad C_{M_{2D}} = \frac{M_{2D}}{\frac{1}{2}\rho V^2 c^2}$ $\quad C_{H_{2D}} = \frac{H_{2D}}{\frac{1}{2}\rho V^2 c_f^2}$

$Re = \frac{\rho V c}{\mu}$ $\quad M = \frac{V}{a}$ $\quad Fr = \frac{V}{\sqrt{gl}}$

Force/moment coefficients may also be rewritten using $\frac{1}{2}\rho V^2 = \frac{1}{2}\gamma p M^2$

Aircraft performance computed using parabolic drag, where $C_D = C_{D_0} + kC_L^2$

For estimating air density at an altitude H in kilometers: $\rho = \rho_0\sigma$ where $\sigma = \frac{20-H}{20+H}$

$$\frac{p_{\infty_{cruise}}}{p_{\infty_{land}}} = \frac{C_{L_{max}}\frac{1}{2}\gamma M_{land}^2}{C_{L_{cruise}}\frac{1}{2}\gamma M_{cruise}^2}$$

$$\begin{aligned}\eta_{total} = \eta_{thermal}\eta_{propulsive} &= \frac{\text{rate kinetic energy}}{\text{fuel power}}\frac{\text{propulsive power}}{\text{rate kinetic energy}} \\ &= \frac{\frac{1}{2}\left(\dot{m}_e u_e^2 - \dot{m}_o u_o^2\right)}{\dot{m}_f h}\frac{Tu_0}{\frac{1}{2}\left(\dot{m}_e u_e^2 - \dot{m}_o u_o^2\right)}\end{aligned}$$

$$u(t) = k_p e(t) + k_i\int_0^t e(t')dt' + k_d\frac{de}{dt}$$

For a potential flow source (+ve source), $u = \frac{\Lambda(x-x_s)}{2\pi((x-x_s)^2+(y-y_s)^2)}$ and $v = \frac{\Lambda(y-y_s)}{2\pi((x-x_s)^2+(y-y_s)^2)}$

For a potential flow vortex (+ve clockwise), $u = \frac{\Gamma(y-y_v)}{2\pi((x-x_v)^2+(y-y_v)^2)}$ and $v = -\frac{\Gamma(x-x_v)}{2\pi((x-x_v)^2+(y-y_v)^2)}$

For a potential flow doublet/circle (pointing right to left), $u = -\frac{\kappa((x-x_d)^2-(y-y_d)^2)}{2\pi((x-x_d)^2+(y-y_d)^2)^2}$ and $v = -\frac{\kappa(x-x_d)(y-y_d)}{\pi((x-x_d)^2+(y-y_d)^2)^2}$

Q1 A vehicle has a drag coefficient of 0.3 based on a reference area of 2.3m^2. Driving at sea level where air density is 1.225kgm^{-3} at a speed of 27ms^{-1}, the drag coefficient increases by 5% if the windows are opened. What is the increase in drag in N if the windows are opened?

[1 marks]

Q2 From the options given, what does direct lift control do? (choose all that apply)

- Directs lift horizontally
- Controls wing area using flaps
- **Alters lift using spoilers**
- Changes aircraft pitch

[1 marks]

Q3 A constant velocity gearbox is fitted to drive the generator mounted on a turbofan engine because: (choose all that apply)

- **the frequency of the AC supply needs to be kept constant**
- the generator may need to be switched off
- the generator is not directly connected to the engine
- **the torque supplied to drive the generator must be variable**

[2 marks]

Q4 An atomic clock is not required in a satellite navigation handset because (choose all that apply)

- Quartz clocks are accurate enough
- **With sufficient time-of-flight measurements there must be a single intersection point**
- Data from the satellite transmissions includes local satellite time
- Actual time is available from Earth-based transmissions

[2 marks]

Q5 Figure 1 shows the influence of vortex generators on the performance of an aerofoil, in terms of C_L and C_D (note these are plotted on separate axes). Assume all other factors remain unchanged.

(a) When vortex generators are used the stall speed of the aerofoil will reduce by what percentage?

(b) For cruise at a C_L of 0.5, would you use vortex generators?

(c) For cruise at a C_L of 1.2 would you use the vortex generators?

[2 marks]

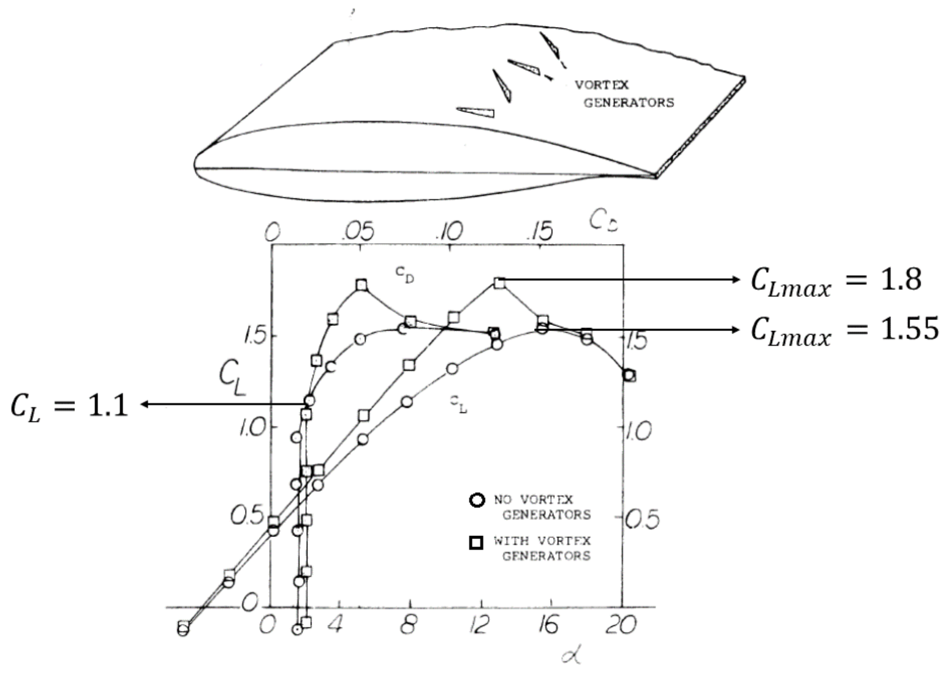

Figure 1: Influence of vortex generators

Stall speed will reduce by factor of $\sqrt{\frac{1.55}{1.8}}$, so reduction of 7.2%. For a C_L of 1.1 the drag curves swap, so for 1.2 VGs should be used, and for 0.5 they should not.

Q6 A particular plain flap control requires a hinge moment coefficient of 0.15 to deflect 15° at speed v_{plain}, and when fitted with a balance panel and geared tab this falls to 0.025 for a speed v_{tab}. What is the ratio $\frac{v_{tab}}{v_{plain}}$ that makes the hinge moment the same for both?

[3 marks]

$$\sqrt{\frac{0.15}{0.025}} = 2.45$$

Q7 A full scale aircraft operates at a Reynolds number of 3×10^6. A 1/10th scale model of the aircraft is constructed for use in a wind tunnel at 1/3rd of the flight speed. How many times smaller must the viscosity of the air in the tunnel be to achieve the flight Reynolds number?

[2 marks]

30

Q8 Both the ship designs in figure 2 are sailing at a speed of v_s through stationary water. The aerodynamic drag coefficients are given in the figure. There are headwinds $v_{w_{lm}}$ (on the 'London mariner design') and $v_{w_{sd}}$ (on the 'streamline design') defined in the fixed frame of reference for each ship, blowing exactly against the direction of both ships' motion, which are different for each ship.

Find an algebraic expression for the ratio $\frac{v_{w_{sd}}}{v_{w_{lm}}}$ of wind speeds that makes the aerodynamic drag of both ships the same, if the headwind on the London mariner configuration is 3 m/s. Assume both ships have the same drag reference area and that all other conditions match between the two ships.

[9 marks]

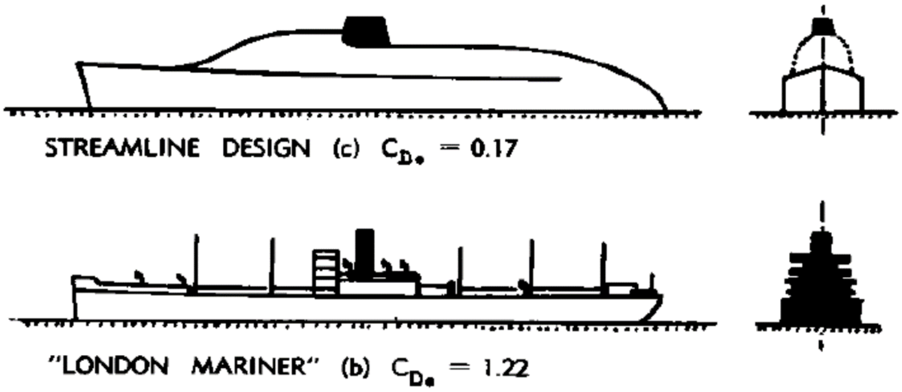

Figure 2: Ship drag coefficients

$$1.22\,(v_s+3)^2 = 0.17\,(v_s+v_w)^2 \tag{1}$$

$$\sqrt{1.22}\,(v_s+3) = \sqrt{0.17}\,(v_s+v_w) \tag{2}$$

$$\frac{v_{w_{sl}}}{v_{w_{lm}}} = \frac{\sqrt{1.22}-\sqrt{0.17}}{\sqrt{0.17}\frac{3}{v_s}} + \frac{\sqrt{1.22}}{\sqrt{0.17}} \tag{3}$$

Q9 The drag force on a small sphere at very low flow speeds was calculated by Stokes as $D = 6\pi\mu R v_\infty$, where μ is dynamic viscosity, R is radius and v_∞ is freestream speed, using SI units.

(a) Derive an expression for the drag coefficient based on frontal area πR^2, and give the name of the resulting non-dimensional number on which it depends.

(b) Calculate the equilibrium speed at which a bubble of gas with radius 0.25×10^{-3}m rises, if the buoyant force is $\frac{4}{3}\rho g \pi R^3$ where $\rho = 1000$kgm^{-3} and $\mu = 0.001$PaS.

[8 marks]

$$C_D = \frac{6\pi\mu R v_\infty}{\frac{1}{2}\rho v_\infty^2 \pi R^2} = \frac{12}{Re_r} \tag{4}$$

so C_D depends on Reynolds number Re_r.

$$\rho h \frac{4}{3}\pi R^3 = 6\pi\mu R v \tag{5}$$

so $v = 13.6$cm/s.

Q10 Figure 3 shows a conventional planform aircraft (wing and tailplane) and exactly the same configuration reversed to fly as a canard. The aspect ratios of the wing and tailplane/foreplane are the same, and the tailplane/foreplane has a chord half the length of the wing chord. Lifting surface positions are as indicated. Assuming the wing and tailplane/foreplane have the same lift gradients, that the aerodynamic centre of any lifting surface is located at 25% of its own local chord, and that there is no aerodynamic interaction between lifting surfaces, calculate the distance of the neutral point of each configuration back from the nose, x_{np1} and x_{np2}. Calculate $x_{np1} + x_{np2}$ and compare this value to the total fuselage length, explaining any difference.

[10 marks]

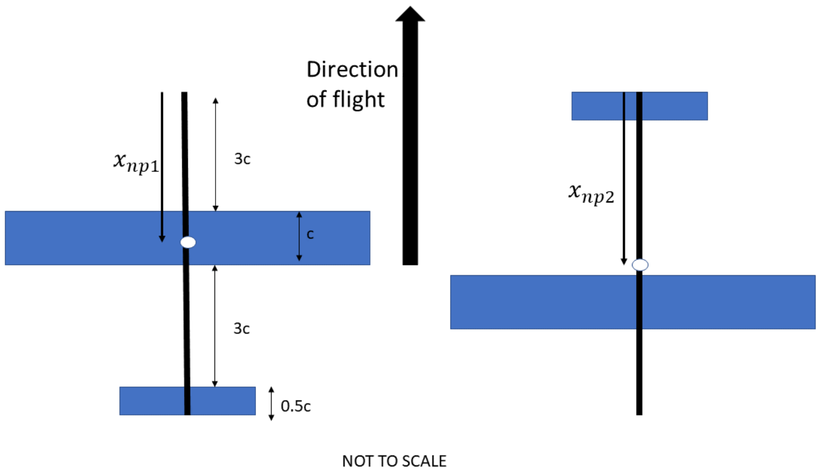

Figure 3: Conventional and canard configurations

Assuming equal lift gradients between the surfaces (reasonable since their aspect ratios match in this case) then

$$x_{np} = \frac{A_w x_{acw} + A_t x_{act}}{A_w + A_t} \tag{6}$$

giving $x_{np1} = 4.025$ and $x_{np2} = 3.025$. $x_{np1} + x_{np2}$ is not equal to the total fuselage length because the local aerodynamic centres are located forward of mid-chord, 25% in this example.

Q11 As shown in figure 4, Naval ships often sail parallel and close together when refuelling, and there is an observed force that tends to pull them together as the separation reduces between them. By evaluating pressure coefficient at (2,0) with a single source located at (0,-7) and comparing to pressure coefficient with two sources located at (0,7) and (0,-7), as shown in figure 4, propose an explanation for the force. You may assume a flow speed of 7ms^{-1} and that the ships are modelled as two-dimensional sources, 10m wide at the farfield limit. For a potential flow source, $u = \frac{\Lambda(x-x_s)}{2\pi((x-x_s)^2+(y-y_s)^2)}$ and $v = \frac{\Lambda(y-y_s)}{2\pi((x-x_s)^2+(y-y_s)^2)}$.

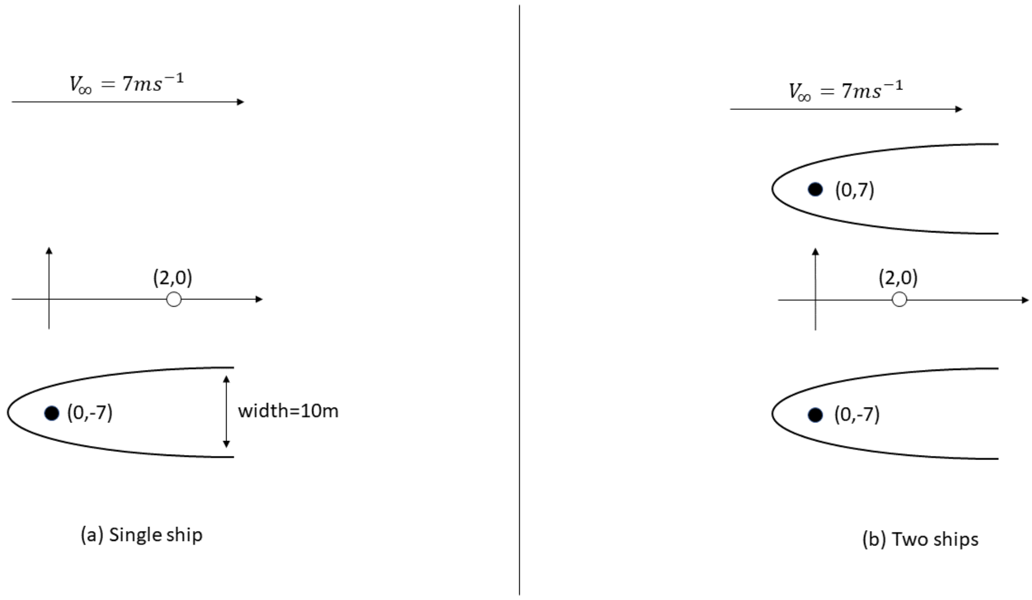

Figure 4: Potential flow models of ships

Source strength is

$$\Lambda = 10 \times 7 = 70m^2s^{-1} \tag{7}$$

Velocity for case 1 is

$$u = 7 + \frac{70(2-0)}{2\pi\left((2-0)^2 + (0+7)^2\right)} = 7 + 0.42 = 7.42 \tag{8}$$

$$v = \frac{70(0+7)}{2\pi\left((2-0)^2 + (0+7)^2\right)} = 1.47 \tag{9}$$

Using $C_p = 1 - \left(\frac{v}{v_\infty}\right)^2$ gives a C_p of -0.17.

When there are two sources, clearly we have $u = 7 + 2 \times 0.42 = 7.84$ while $v = 0$ by symmetry, which gives $C_p = -0.25$. The pressure in the region between the ships is therefore notably lower as a result of interference between them. This lower pressure tends to pull them together.

[10 marks]

Q12 Figure 5 shows a simplified sketch of the vertical load distribution on a wing with an engine and winglet, where it is assumed that the distributed load on the wing and winglet is uniform and equal. The overall wing lift coefficient is C_L . Air density is ρ and airspeed is V. Find an algebraic expression for the wing root bending moment M and shear force F as indicated at the centreline of the fuselage. Also write down an expression for w in terms of C_L, dynamic pressure, (single) wing area S and semi-span L.

[10 marks]

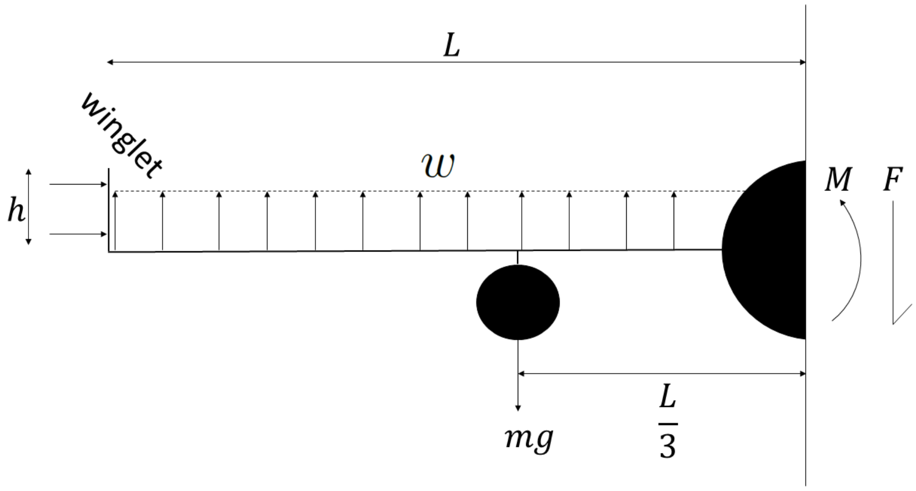

Figure 5: Wing loading sketch

$$M = \frac{wL^2}{2} - mg\frac{L}{3} + \frac{wh^2}{2} \tag{10}$$

$$F = wL - mg \tag{11}$$

$$w = \frac{C_L \frac{1}{2}\rho V^2 S}{L} \tag{12}$$

Q13 Consider an unmanned, solar powered, very high aspect ratio tailless aircraft similar to the AeroVironment/NASA Helios shown in figure 6. Assume the aircraft has the following characteristics: m = 900 kg, S = 184 m^2, AR = 30.9, e = 0.87, C_{D_0} = 0.025. It has 14 electric motors with a maximum power output of 1.5 kW each.

Figure 6: The Helios solar powered UAV

(a) Find the induced drag factor K

[2 marks]

$$K = \frac{1}{\pi ARe} = 0.01184 \tag{13}$$

(b) If this aircraft can fly at an equivalent airspeed of V_E = 9 m/s at an extreme high altitude of 25 km where the air density is 0.04 kgm^{-3}, what will its ground speed be (assuming still air)? What percentage of the total available motor power must the Helios use to fly at this speed (ignore propeller efficiency losses)?

[6 marks]

Speed at 25 km will be $9 \div \sqrt{\frac{0.04}{1.225}} = 49.8m/s$.

$$P = \left(C_{D_0} + KC_L^2\right)\frac{1}{2}\rho V^3 S = 16.4kW \tag{14}$$

which is 78.1% of max power.

(c) In part (b) above, what is the underlying physical reason why it would have been incorrect to use the simple density scaling factor equation for estimating the air density at 25 km altitude: $\sigma = \frac{20-H}{20+H}$?

[4 marks]

The approximation is only valid in the Troposphere, and 25km is well into the Stratosphere.

(d) If the Helios were flying at sea level and the motors suddenly lost power, what speed should it fly at to maximise the distance it can travel?

[4 marks]

C_L for best L/D is then 1.453 giving

$$V = \sqrt{\frac{900 \times 9.81}{C_L \times 0.5 \times 1.225 \times 184}} = 7.34m/s \tag{15}$$

(e) What impact do you think the highly bent wings will have on the aerodynamics of this aircraft? What about its stability?

[4 marks]

Thrust and drag are vertically distributed, allowing pitch control. Greater pitching moment of inertia slowing any instabilities, or giving longer frequency SPPO. Limited influence on spanload as twist probably small, but there will be some change due to non-planar downwash field. Essentially, effective aspect ratio drops as bending reduces span.

Q14 The Breguet range R for propeller driven aircraft is given by:

$$R = \frac{\eta}{fg}\frac{C_L}{C_D}\ln\left(\frac{W_1}{W_2}\right)$$

The Breguet formula for endurance E of a propeller powered aircraft is given by:

$$E = \frac{\eta}{fg}\frac{1}{V}\frac{C_L}{C_D}\ln\left(\frac{W_1}{W_2}\right)$$

(a) Explain how and why these two equations differ from their jet powered aircraft equivalents.

[5 marks]

Props give power specific fuel consumption, while jets are thrust specific. This means jets have optimum range at a higher speed (lower C_L).

A propeller driven cargo aircraft has a wing area of S = 225 m^2, a drag polar given by $C_D = 0.028 + 0.045 C_L^2$, a propeller efficiency of η = 80%, and a specific fuel consumption of f = 5.5 x 10^{-8} kg/Ws. The aircraft has an empty weight of 76,500 kg and has just performed an in-flight refuelling and is carrying 30,000 kg of fuel.

(b) What is the maximum range obtainable by this aircraft when starting at sea level assuming it retains an emergency fuel reserve of 10%?

[5 marks]

C_L for max range is $\sqrt{\frac{0.028}{0.045}} = 0.789$ and best L/D of 14.09. Range is then $\frac{0.8}{5.5\times10^{-8}\times9.81} \times 14.09 \ln\left(\frac{106500}{79500}\right) = 6106km.$

(c) What true airspeed must the aircraft fly at to obtain this maximum range at sea level? At this speed, what percentage of the total drag will be induced drag?

[4 marks]

Speed would be $\sqrt{\frac{106500g}{0.789\times0.5\times1.225\times225}} = 98m/s$. At best L/D, half of drag is induced drag.

(d) If it is free to fly at any speed, what is the maximum amount of time (in hours) that this aircraft can stay airborne at an initial altitude of 10 km (no fuel reserve)?

[6 marks]

Shift to min power $C_L = \sqrt{\frac{3C_{D_0}}{K}}$ of 1.366. Then $\frac{L}{D} = \frac{C_L}{C_{D_0}+KC_L^2} = 12.198$, speed at altitude where density is 0.408kg/m3 is $\sqrt{\frac{106500g}{1.366\times0.5\times0.408\times225}} = 129.0m/s$, and endurance $\frac{0.8}{5.5\times10^{-8}\times9.81}\frac{1}{129.0}12.198\ln\left(\frac{106500}{76500}\right) = 12.88hrs$

END OF PAPER